Αρχηαγγελοσ

Archangel v3.2

for MatLab

User's Manual

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1. Introduction

Where shall we begin? At the beginning, of course! This is a short history of the development of Archangel as an aircraft design analysis tool for the students of the Aerospace Engineering Department of California Polytechnic State University, San Luis Obispo.

In 1983, student Mark Anderson developed software called Flight.f to calculate aircraft plant matrices from aircraft test data. This proved very useful to Cal Poly aeronautical engineering students in that it relieved them of the burden of calculating these matrices by hand. This software was updated in 1992. By 1993, desktop computers had advanced in computing power to the point where more complex calculations could be rapidly performed. So in that year, Archangel 1.0 was developed to extend the calculations to include analysis tools.

Since then, Archangel has evolved through several iterations of independent student coding to become a fundamental tool for aerospace engineering students to use in all phases of aircraft and spacecraft design. Undergraduate student Mark Morrel originally wrote the MatLab© version of Archangel when he became frustrated with the limitations of the burdensome Archangel v2.0. He released his Archangel as version 2.5.

Over the past year, I optimized and expanded upon v2.5 to such a point as to release it as version 3.0. Several of the original MatLab m-files were modified/re-used. This version, 3.2, is the final version ready for release to the engineering publicly. Stay in touch with Dr. Dan Biezad for future updates, one of which will include a GUI interface!

Kenneth Bole
CPSLO, Spring 2001

2. Installation and Start Up

To install Archangel 3.2, copy the file "Archangel3_2.exe" to the "toolbox" directory under your main MatLab directory. Open the self-extracting zip file by double-clicking it. This will create and copy the following m-files to a new ".\toolbox\Archangel3_2" directory.

AAV3.m	BANDW.m	BANDW1.m	BANDW2.m
BANDWHEL.m	da_ResMatrix1.m	damp2.m	de_ResMatrix.m
DelayDRResMenu.m	DelayMenu.m	DelayPhResMenu.m	DelayResTF.m
DelayRollResMenu.m	DelaySpiralResMenu.m	DelaySPResMenu.m	DispDelayTF.m
DisplayPFE.m	DLATP.m	DLATSS.m	DLATTFA.m
DLATTFR.m	DLONGP.m	DLONGSS.m	DLONGTF.m
dr_ResMatrix1.m	DRResCompare.m	DSBP.m	DSNP.m
DSRLP.m	DSSIGGY.m	DSSRP.m	EigRes.m
FQA.m	GRAPHIC.m	GRAPHIC2.m	LAT_R_SMITH.m
LATFQA.m	LATPAR.m	LatResidues.m	LATSS.m
LATTFA.m	LATTFR.m	LONG_R_SMITH.m	LONGPAR.m
LongResidues.m	LONGSS.m	LONGTF.m	N_SMITH.m
N_SMITH1.m	NCARPET.m	newOPTION.m	NORMALIZE.m
NSDROOP.m	NSPEAK.m	PhResCompare.m	residudispmenu.m
residumenu.m	RollResCompare.m	SIGGY.m	SpiralResCompare.m
SPResCompare.m			

It will also copy the following SAD files to the same directory.

747_catB_a.SAD	747_catB_b.SAD	747_catC.SAD
A1.SAD	A4.SAD	A4D_catB.SAD
A4D_catC.SAD	BeechM21_catB_a.SAD	BeechM21_catB_b.SAD
BeechM21_catC.SAD	c880_catB.SAD	c880_catC.SAD
Cessna172_catB.SAD	f104_catB.SAD	f104_catC.SAD
F4C_catB_a.SAD	F4C_catB_b.SAD	F4C_catC.SAD
Jetstar_catB.SAD	Jetstar_catC.SAD	Learjet_catB_a.SAD
Learjet_catB_b.SAD	Learjet_catC.SAD	Marchetti211_catB_a.SAD
Marchetti211_catB_b.SAD	Marchetti211_catC.SAD	navion_catB.SAD
STOL_catB.SAD	STOL_catC.SAD	

Add Archangel directory to MatLab Path

The next step is to add this new directory to the path in MatLab.

1. Open MatLab. Under the "File" menu, select "Set Path…".
2. In the Path Browser window, under the "Path" menu, select "Add to Path…"
3. On the "Add to Path" window, click the "…" button, browse to and select the "Archangel3" directory created before
4. Ensure the "Add to back" radio button is selected, then click the "OK" button
5. Finally, under the Path Browser "File" menu, select "Save Path"
6. Close the Path Browser

Standard Aircraft Data (SAD) files

Archangel also needs at least one Standard Aircraft Data (SAD) file available in any directory contained in the MatLab path. This is because the first piece of information Archangel asks for is the name and extension of a SAD file. You can either enter one by hand or use one already in existence. If you choose to enter the data in a SAD file by hand, open a blank text file and enter the data in the following order (i.e., Roskam format):

Flight Condition

1) Altitude (ft)
2) Air Density (slugs/ft^3)
3) Speed (fps)
4) Initial Attitude (θ_1 in rad)

Geometry and Inertias

5) Wing Area (ft^2)
6) Wing Span (ft)
7) Wing Mean Aerodynamic Chord ($\bar{c}$, ft)
8) Weight (lbs)
9) I_{xx} (slug-ft^2)
10) I_{yy} (slug-ft^2)
11) I_{zz} (slug-ft^2)
12) I_{xz} (slug-ft^2)

Steady State Coefficients

13) C_{L_1}
14) C_{D_1}
15) $C_{T_{X_1}}$
16) C_{m_1}
17) $C_{m_{T_1}}$

Longitudinal Directional Derivatives

18) C_{m_u}
19) C_{m_α}
20) $C_{m_{\dot{\alpha}}}$
21) C_{m_q}
22) $C_{m_{T_u}}$

23) $C_{m_{T\alpha}}$

24) C_{L_u}

25) C_{L_α}

26) $C_{L_{\dot{\alpha}}}$

27) C_{L_q}

28) C_{D_α}

29) C_{D_u}

30) $C_{T_{X_u}}$

31) $C_{L_{\delta_e}}$

32) $C_{D_{\delta_e}}$

33) $C_{m_{\delta_e}}$

Lateral Directional Derivatives

34) C_{ℓ_β}

35) C_{ℓ_p}

36) C_{ℓ_r}

37) $C_{\ell_{\delta_a}}$

38) $C_{\ell_{\delta_r}}$

39) C_{n_β}

40) C_{n_p}

41) C_{n_r}

42) $C_{n_{\delta_a}}$

43) $C_{n_{\delta_r}}$

44) C_{y_β}

45) C_{y_p}

46) C_{y_r}

47) $C_{y_{\delta a}}$

48) $C_{y_{\delta r}}$

If you don't have data for some of the line items, enter a zero (0) for these items. When you're finished entering the data, for standardization purposes save SAD files with a ".SAD" extension. That way you will always know what the file contains.

Archangel Main Help

Help is available for Archangel by typing 'help AAV3' in the MatLab Workspace. This help will list the names of most of the variables used for calculation along with their explanation; all the variables used throughout Archangel are listed in Appendix A. Once calculated, you can escape to the MatLab command line and use other MatLab analysis tools on these variables, such as those in the Aerocontrols toolbox.

Start Archangel

Now you are ready to begin using Archangel 3. Start it by opening MatLab and typing 'AAV3' in the MatLab command window. Hit the "Enter" key when it pauses. Then, enter the full name, including file extension, of the aircraft SAD file you want to analyze. Next, it will ask you for the Aircraft Class Group of the aircraft; see Table 1 for a breakdown of these classes.

Class I	Small, light airplanes, such as light utility, primary trainer, and light observation craft
Class II	Medium-weight, low-to-medium maneuverability airplanes, such as heavy utility/search and rescue, light or medium transport/cargo/tanker, reconnaissance, tactical bomber, heavy attack and trainer for Class II (NOTE: A *C* extension is for aircraft in nonterminal flight phases, while an *L* is for terminal.)
Class III	Large, heavy, low-to-medium maneuverability airplanes, such as heavy transport/cargo/tanker, heavy bomber and trainer for Class III
Class IV	High-maneuverability airplanes, such as fighter/interceptor, attack, tactical reconnaissance, observation and trainer for Class IV

Table 1. Classification of airplanes

Archangel has separated the classes into two groups for calculations made during additional analyses. Group 1 contains classes I, II-C, and IV; group 2 contains classes II-L and III. Enter the number of the group to which the aircraft you want to analyze belongs.

Next, you will be asked to select the category of flight phase the aircraft was in when the SAD file data was measured; see Table 2 for flight phase categories.

Nonterminal flight phase	
Category A	Nonterminal flight phase that require rapid maneuvering, precision tracking, or precise flight-path control. Included in the category are air-to-air combat, ground attack, weapon delivery/launch, aerial recovery, reconnaissance, in-flight refueling (receiver), terrain-following, antisubmarine search, and close-formation flying
Category B	Nonterminal flight phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Included in the category are climb, cruise, loiter, in-flight refueling (tanker), descent, emergency descent, emergency deceleration, and aerial delivery.
Terminal flight phases	
Category C	Terminal flight phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Included in this category are takeoff, catapult takeoff, approach, wave-off/go-around and landing.

Table 2. Flight phase categories

Enter the number corresponding to the flight phase of the aircraft. Now, Archangel will make several calculations, then display the main Archangel menu (Figure 1).

```
**********************************************************************
**********************************************************************
YOUR MAIN OPTIONS ARE:
(1)  Display Longitudinal State Space Model (Full State Feedback)
(2)  Display Longitudinal Transfer Functions in Zero-Pole-Gain Format
(3)  Display Longitudinal Parameters
(4)  Display Lateral State Space Model (Full State Feedback)
(5)  Display Aileron Lateral Transfer Functions in Zero-Pole-Gain Format
(6)  Display Rudder Lateral Transfer Functions in Zero-Pole-Gain Format
(7)  Display Lateral Parameters
(8)  Display Selected Bode Plots With Wc, PM, and GM Indicated
(9)  Display Selected Root Locus Plots
(10) Display Selected Open-Loop Step Responses
(11) Display Selected Nichols Plots
(12) Display Selected Siggy Plots
(13) Longitudinal Handling Qualities Analysis With THETA/DEP Transfer Function
(14) Lateral-Directional Handling Qualities Analysis
(15) Residue and additional analyses
(16) Select another SAD file
(17) To Escape to MatLab command line
(18) Exit MatLab
**********************************************************************
Please Enter A Number Corresponding To An Option Above:
```

Figure 1. Archangel main menu

Archangel 3.2 is a menu driven system. Type the number next to the function you want it to perform, then hit the "Enter" key. For details on options 1 through 15, see the sections in this manual as listed below.

Main Menu Options	Section
1, 2, 3, and 13	3 (Longitudinal Analyses)
4, 5, 6, 7, and 14	4 (Lateral Analyses)
8, 9, 10, 11, and 12	5 (Graphical Analyses)
15	6 (Residue and Additional Analyses)

Option 16 resets all the calculation variables and allows you to select a different SAD file for analysis. Option 17 allows you to escape to the MatLab command line. Option 18 exits MatLab altogether.

3. Longitudinal Analyses

Archangel Main Menu Option 1 - Longitudinal state-space model display
When you select option 1 from the Archangel main menu, it will display the longitudinal state-space model of the aircraft, i.e., A, B, C, and D matrices. An example of this display is shown in Figure 2.

```
Longitudinal State-Space System (Along,Blong,Clong,Dlong):

A =                    u        alpha        theta            q
           u     -0.04422     18.74408    -32.20000            0
       alpha     -0.00135     -2.20202            0      0.97925
       theta            0            0            0      1.00000
           q      0.00244    -23.72524            0     -6.13122


B =                   De
           u     -6.24803
       alpha     -0.20446
       theta            0
           q    -39.48824


C =                    u        alpha        theta            q
           u      1.00000      1.00000      1.00000      1.00000


D =                   De
           u            0
```

Figure 2. Archangel display of longitudinal state-space matrices

These matrices come from the state variable equations

$$\dot{x} = Ax + B\eta$$
$$y = Cx + D\eta$$

where x is the state vector, η is the control input vector, and y is the output vector. The A matrix is the aircraft or plant matrix, B is the control input matrix, C is the output matrix multiplier of the state vector, and D is the output matrix multiplier of the control vector.

For the longitudinal state-space representation, x consists of states in the following order: u (velocity), α (angle of attack), θ (pitch angle), and q (pitch rate). The control input vector, η, only reflects one input, δ_e, which is the elevator deflection.

Archangel Main Menu Option 2 - Longitudinal transfer functions display
When you select option 2 from the Archangel main menu, it will display all the longitudinal transfer functions for the aircraft in zero-pole-gain format over two screens. The u/δ_e and α/δ_e transfer functions are shown first, after which Archangel waits for you to press the "Enter" key. After you do, the θ/δ_e, q/δ_e, and nz/δ_e transfer functions are displayed,

whereupon there is another pause. Press the "Enter" key to continue. See Figure 3 for an example of how Archangel displays the transfer functions.

```
u/de

Zero/pole/gain:
       6.248 (s+8.865) (s+6.95) (s-6.868)
-----------------------------------------------
(s^2 + 0.04192s + 0.03269) (s^2 + 8.336s + 36.75)



alpha/de

Zero/pole/gain:
  0.20446 (s+195.2) (s^2 + 0.04309s + 0.04329)
-----------------------------------------------
(s^2 + 0.04192s + 0.03269) (s^2 + 8.336s + 36.75)
```

Figure 3. Archangel display of longitudinal transfer function

Archangel Main Menu Option 3 - Longitudinal parameters display

When you select option 3 from the Archangel main menu, it will display two screens of parameters associated with aircraft longitudinal motion. The first screen will show the Control Anticipation Parameter (CAP), $1/T_{\theta_2}$ (the pitch rate time constant), and n/α (g's to angle of attack ratio). When done with the information on this screen, type the "Enter" key to proceed to the next.

The second screen will show the short period frequency (approximate and actual), short period damping ratio (approximate and actual), the phugoid frequency (approximate and actual), and the phugoid damping ratio (approximate and actual). See Figure 4 for an example of this screen.

```
                        Approximate   Actual
                        -----------   -------
Short Period frequency:    5.2686     6.0618
Short Period damping:      0.79085    0.68754


                    Approximate   Actual
                    -----------   -------
Phugoid frequency:    0.2082      0.18081
Phugoid damping:      0.0708      0.11592
```

Figure 4. Archangel display of short period and phugoid parameters

Archangel Main Menu Option 13 - Longitudinal Handling Qualities Analysis

When you select option 13 from the Archangel main menu, a warning is displayed regarding the error that occurs in the bandwidth criterion when a low order system's phase does not cross -180°. Also, enter the amount of delay you want to add to the closed-loop system analyses (Smith-Geddes, Neal-Smith, and Mil-Std Bandwidth). *You must enter a non-zero, non-negative value*.

After making the necessary calculations, a new menu is displayed with all the handling quality analyses. Each analysis is followed by a calculated flying qualities rating based on the selected criterion. See Figure 5 for an example of this menu.

```
**********************************************************************
LONGITUDINAL FLYING HANDLING QUALITIES ANALYSIS MENU
**********************************************************************
(1)  Smith-Geddes Criterion Yields LEVEL:  1

(2)  Neal-Smith Criterion Yields LEVEL:  1

(3)  MIL-STD Bandwidth Criterion Yields LEVEL:  2

(4)  MIL-STD CAP Criterion Yields LEVEL:  1

(5)  MIL-STD (wnsp,ttheta2) Criterion Yields LEVEL:   1

(6)  MIL-STD Closed-Loop Criterion Yields LEVEL: 1

(7)  Northrop Criterion Yields LEVEL:  1

(8)  Smith Geddes PIO Criterion Yields LEVEL:  1

(9)  Look at Neal-Smith Carpet Plot (BW and DROOP Varied)
(10) Compare Frequency Response of Nominal and Delayed Theta/DEP
(11) Return to Archangel Main Menu
**********************************************************************
Please Enter a Number Listed Above to View a Graphical Analysis:
```

Figure 5. Longitudinal handling qualities menu

Ratings are given on a three level basis and rated by pilots during flight testing. A level 1 rated aircraft is clearly adequate for the mission flight phase. Aircraft rated level 2 are adequate for the mission flight phase, but with some increase in pilot workload, degradation in mission effectiveness, or both. Level 3 aircraft can be safely controlled by the pilot, but workload is excessive, mission effectiveness is inadequate, or both.

The parameters that each criterion bases its analysis upon differs, which leads to the different ratings. Generally, four of the criteria (Smith-Geddes, Neal-Smith, Mil-Std Bandwidth, Mil-Std Closed Loop, and Smith-Geddes w/ PIO) should only be used to analyze closed loop systems. The remaining criteria (Mil-Std CAP, Mil-Std (wnsp, ttheta2), Northrop) may only be used to analyze open-loop systems.

As indicated at the bottom of the screen, each of the menu items may be selected for graphical analysis upon which each criterion is based. Type the number of the desired option, and press the “Enter” key. When finished examining any of the graphical analyses, press the “Enter” key to close the graph window and continue.

To return to the Archangel main menu, select option 11.

4. Lateral Analyses

Archangel Main Menu Option 4 - Lateral state-space model display
When you select option 4 from the Archangel main menu, it will display the lateral state-space model of the aircraft, i.e., A, B, C, and D matrices. An example of this display is shown in Figure 6.

```
Lateral-Directional State-Space System (Alat,Blat,Clat,Dlat):

A =                 Beta          phi            p           si            r
        Beta     -0.14740      0.14703     -0.00144            0     -0.99184
         phi            0            0      1.00000            0            0
           p    -28.74922            0    -12.40917            0      2.53464
          si            0            0            0            0      1.00000
           r     10.11937            0     -0.38174            0     -1.25975


B =                   dA           dR
        Beta           0      0.08892
         phi           0            0
           p    57.49844      4.74847
          si           0            0
           r    -8.25118    -10.22835


C =                 Beta          phi            p           si            r
        Beta     1.00000      1.00000      1.00000      1.00000      1.00000


D =                   dA           dR
        Beta           0            0
```

Figure 6. Archangel lateral state-space matrices

The *x* vector for the lateral state-space representation consists of states in the following order: β (side-slip angle), ϕ (roll angle), p (roll rate), ψ (yaw angle), and r (yaw rate). There are two columns in the input vector, η, representing the two input surfaces that affect lateral control. These are δ_a, the aileron deflection, and δ_r, the rudder deflection.

Archangel Main Menu Options 5/6 - Lateral transfer function displays
When you select option 5 or 6 from the Archangel main menu, it will display the lateral transfer functions for the aircraft dependent upon aileron deflection and rudder deflection, respectively. As with the longitudinal transfer functions, each is displayed one after the next. The aileron transfer functions β/δ_a, ϕ/δ_a, p/δ_a, ψ/δ_a, and r/δ_a, and rudder transfer functions β/δ_r, ϕ/δ_r, p/δ_r, ψ/δ_r, and r/δ_r are displayed, whereupon there is another pause. Press the "Enter" key to return to the Archangel main menu. See Figure 3 for an example of how Archangel displays transfer functions.

Archangel Main Menu Option 7 - Lateral parameters display
When you select option 7 from the Archangel main menu, it will show the Dutch roll frequency (approximate and actual), and Dutch roll damping ratio (approximate and actual). See Figure 7 for an example of this screen.

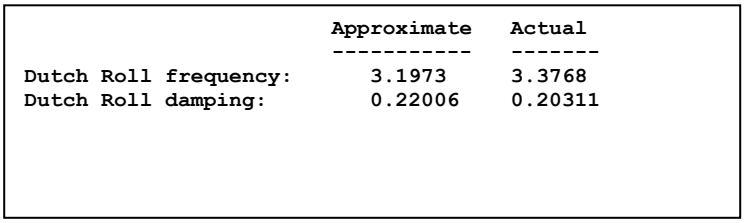

Figure 7. Archangel display of Dutch roll parameters

When done with this information on this screen, type the "Enter" key to return to the Archangel main menu.

Archangel Main Menu Option 14 - Lateral Handling Qualities Analysis

When you select option 14 from the Archangel main menu, you will be asked to enter the amount of delay you want to add to the Smith-Geddes system analyses. *You must enter a non-zero, non-negative value*.

After making the necessary calculations, a new menu is displayed with all the few lateral flying handling quality analyses. The one criteria analysis is followed by a calculated flying qualities rating based on the Smith-Geddes criteria. See Figure 8 for an example of this menu.

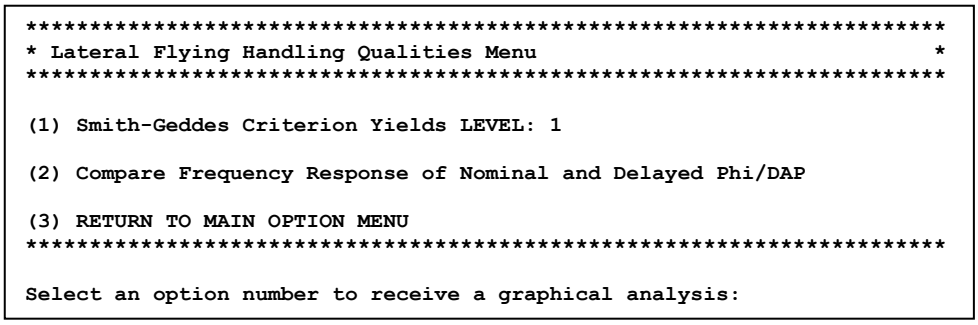
* Lateral Flying Handling Qualities Menu *
(1) Smith-Geddes Criterion Yields LEVEL: 1
(2) Compare Frequency Response of Nominal and Delayed Phi/DAP
(3) RETURN TO MAIN OPTION MENU
Select an option number to receive a graphical analysis:

Figure 8. Lateral flying handling qualities menu

As indicated at the bottom of the screen, each of the menu items may be selected for graphical analysis upon which each criterion is based. Type the number of the desired option, and press the "Enter" key. When finished examining any of the graphical analyses, press the "Enter" key to close the graph window and continue.

Selecting option 1 on this menu will display a graphical analysis of the aircraft on which the Smith-Geddes criteria rating is based. Option 2 will display a Bode plot comparing the normal and delayed system frequency response. When done with these analysis tools, select option 3 to return to the Archangel main menu.

5. Graphical Analyses

Archangel Main Menu Option 8 - Bode Plots
Selecting option 8 from the Archangel main menu will take you to the Bode plot selection menu. Selecting options 1-15 from this menu will display a Bode plot of any of the available aircraft transfer functions:

$$\frac{u}{\delta_e}, \frac{\alpha}{\delta_e}, \frac{\theta}{\delta_e}, \frac{q}{\delta_e}, \frac{nz}{\delta_e}, \frac{\beta}{\delta_a}, \frac{\phi}{\delta_a}, \frac{p}{\delta_a}, \frac{\psi}{\delta_a}, \frac{r}{\delta_a}, \frac{\beta}{\delta_r}, \frac{\phi}{\delta_r}, \frac{p}{\delta_r}, \frac{\psi}{\delta_r}, \frac{r}{\delta_r}$$

Bode plots allow the student to analyze the frequency and phase response of a system simultaneously. See Figure 9 for an example of a Bode plot displayed by Archangel. Option 16 on the Bode plot menu will return you to the "Archangel main menu".

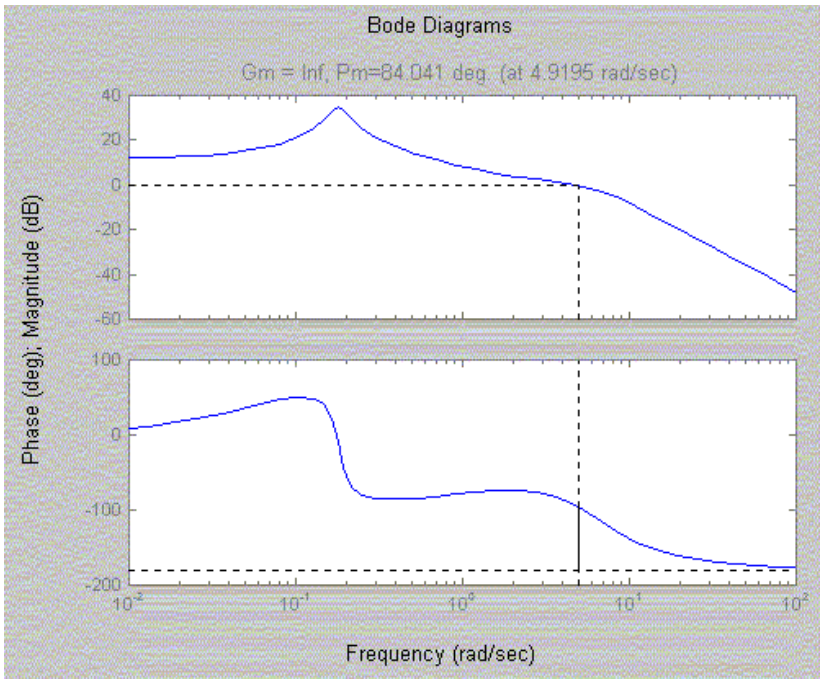

Figure 9. Archangel Bode plot

In addition to this Bode plot function, you can escape from Archangel and use the Aerocontrols "ezbode" command with any of the calculated transfer functions from Archangel. For example, if you wish to view the θ / δ_e transfer function using ezbode, type "ezbode(tf(thtodenum,thtodeden))" at the MatLab command line. The "tf" function turns given numerator and denominator vector matrices into transfer functions for use with other MatLab tools.

Archangel Main Menu Option 9 - Root Locus Plots
This option will open the Root Locus plot selection menu. Selecting options 1-15 from this menu will display a Bode plot of any of the available aircraft transfer functions. Option 16 will return you to the "Archangel main menu".

Root locus plots allow the student to analyze the stability, natural frequency, and damping ratio of a system based on the locations of transfer function poles (marked with an X) and zeroes (marked with a O) on the imaginary plane. See Figure 10 for an example of a Root Locus plot displayed by Archangel.

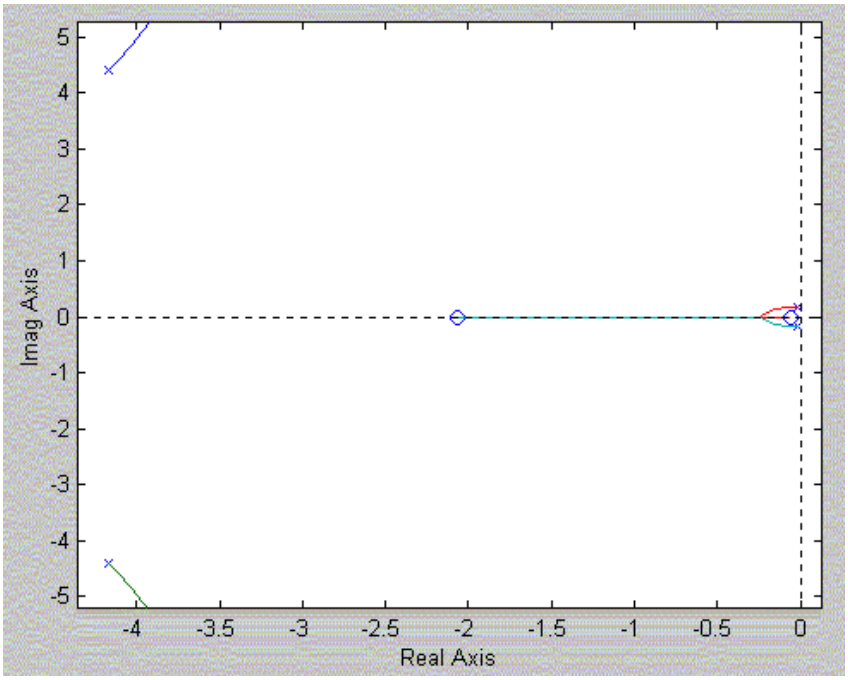

Figure 10. Archangel root locus plot

In addition to this root locus plot function, you can escape from Archangel and use the Aerocontrols "ezrlocus" command with any of the calculated transfer functions from Archangel. For example, if you wish to view the θ / δ_e transfer function using ezrlocus, type "ezrlocus(tf(thtodenum,thtodeden))" at the MatLab command line. The "tf" function turns given numerator and denominator vector matrices into transfer functions for use with other MatLab tools.

Archangel Main Menu Option 10 - Open-Loop Step Response

This option takes you to the step response plot selection menu. Selecting options 1-15 from this menu will display a time step response of the open-loop transfer function chosen. The transfer functions are listed in the same order as on the Bode plot menu. Option 16 will return you to the "Archangel main menu".

The open-loop step response can confirm analyses from other tools, such as the stability of the system and the system damping. It also tells you how long the system will take to respond to an input and how well it will respond. See Figure 11 for an example of an open-loop response plotted by Archangel.

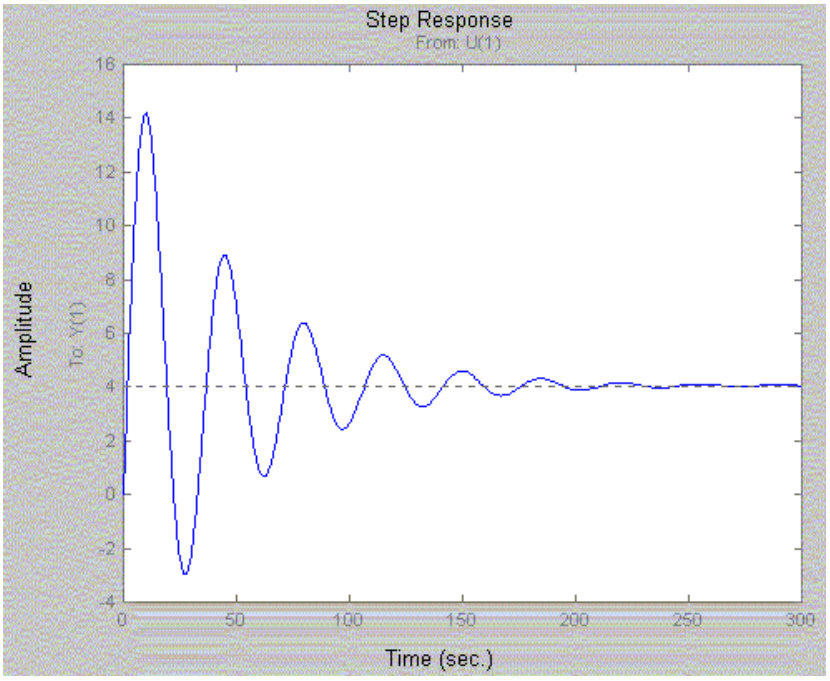

Figure 11. Archangel open-loop time response graph

Archangel Main Menu Option 11 - Nichols Plots

This option takes you to the Nichols plot selection menu. Selecting options 1-15 from this menu will display a Nichols plot of the selected transfer function. The transfer functions are listed in the same order as on the Bode plot menu. Option 16 will return you to the "Archangel main menu".

A Nichols plot is an alternate form of the Bode plot that combines all Bode elements onto one graph. It allows the student, after some practice and experience reading it, to analyze the frequency and phase response of a system. See Figure 12 for an example of an Archangel Nichols plot.

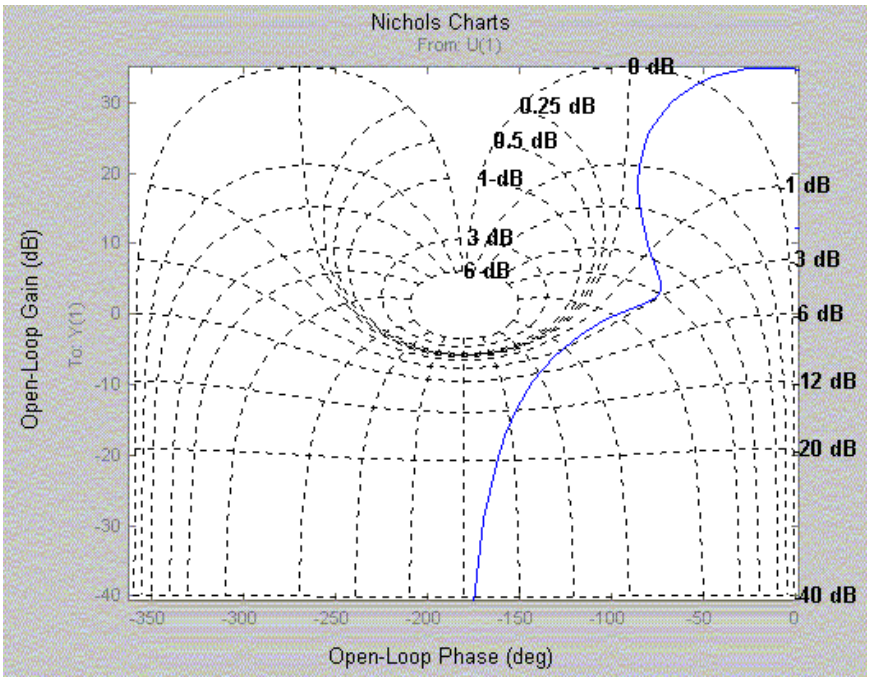

Figure 12. Archangel Nichols plot

Archangel Main Menu Option 12 - Siggy Plots

This option takes you to the Siggy plot selection menu. Selecting options 1-15 from this menu will display a Siggy plot of the transfer function chosen (see Figure 13). The transfer functions are listed in the same order as on the Bode plot menu. Option 17 will return you to the "Archangel main menu".

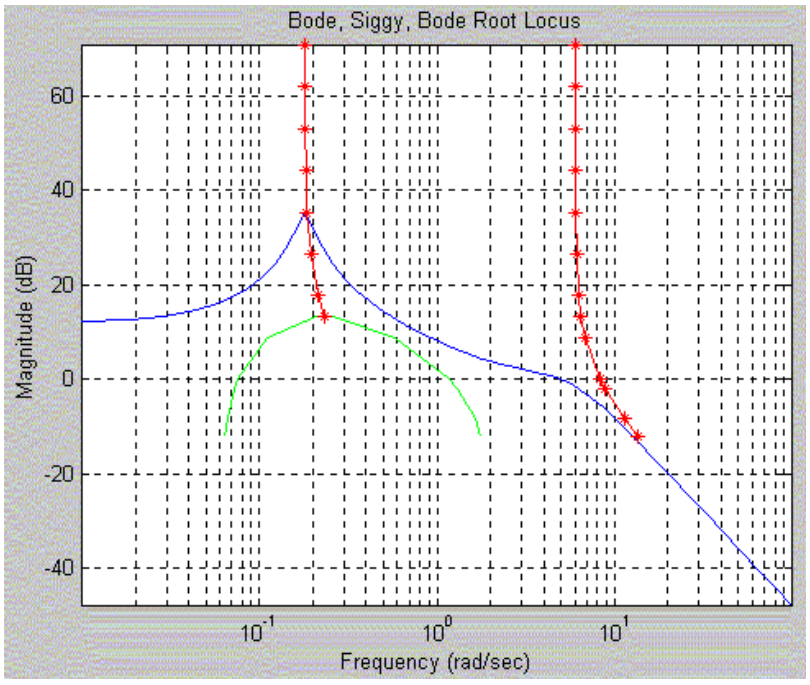

Figure 13. Archangel Siggy plot

6. Residue and Additional Analyses

Selecting option 15 from the Archangel main menu will open the "Residue and Additional Analyses" menu. See figure 14 for an example of this menu.

```
**********************************************************************
RESIDUE AND ADDITIONAL ANALYSES MENU
**********************************************************************
(1)  Display residues and poles
(2)  Display normalized longitudinal residue magnitudes
(3)  Display normalized lateral (aileron) residue magnitudes
(4)  Display normalized lateral (rudder) residue magnitudes

(5)  Display effect of delay on poles
(6)  Display effect of delay on short period residues
(7)  Display effect of delay on phugoid residues
(8)  Display effect of delay on Dutch roll residues
(9)  Display effect of delay on roll residues
(10) Display effect of delay on spiral residues

(11) Display Modal Controllability matrix, Eigenspace and MatLab calculated residues

(12) Return to MatLab workspace
(13) Return to Archangel Main Menu
**********************************************************************
Please Enter A Number Corresponding To An Option Above:
```

Figure 14. Residue and Additional Analyses menu

All available options are detailed below, with the exception of options 12 and 13. As on the other menus, these last two options will exit to the MatLab command line and return you to the Archangel Main Menu, respectively.

Residue and Additional Analyses Option 1 - Display residues and poles
This option takes you to the residue display menu, which lists all 15 transfer functions as display options, as well as options to return to the "Residue and additional analyses" menu and to return to the "Archangel main menu". Each transfer function has its own set of associated residues as calculated in a partial fraction expansion (PFE). When displayed in PFE form, a transfer function looks as follows:

$$\frac{R_1}{(s-\lambda_1)}+\frac{R_2}{(s-\lambda_2)}+\cdots+\frac{R_n}{(s-\lambda_n)}$$

where R_n are the residues and λ_n are the eigenvalues of the A matrix (as well as the roots of the transfer function). Archangel displays the partial fraction expansion as in Figure 15; it is an example of a θ/δ_e PFE display.

```
theta/de

Zero/pole/gain:
          39.4882 (s+2.064) (s+0.05974)
-----------------------------------------------
(s^2 + 0.04192s + 0.03269) (s^2 + 8.336s + 36.75)



theta/de=

      -1.1173-3.4253i
 ------------------------      +
 (s + (4.1678 +4.4018i))


      -1.1173+3.4253i
 ------------------------      +
 (s + (4.1678 -4.4018i))


       1.1173-0.18692i
 -------------------------     +
 (s + (0.02096 +0.17959i))


       1.1173+0.18692i
 -------------------------
 (s + (0.02096 -0.17959i))
```

Figure 15. Archangel residue (partial fraction expansion) display

Residue and Additional Analyses Option 2/3/4 - Display normalized residue matrices

Options 2 through 4 display the residue matrices for each of the control surface inputs numerically and graphically. The longitudinal residue matrix follows the same order as all other longitudinal displays in Archangel: u, α, θ, q. Likewise, the lateral residue matrices: β, ϕ, p, ψ, r. Figure 16 shows a typical normalized residue matrix numerical display.

```
Normalized Longitudinal Residue Magnitudes

                SP1       SP2       Ph1       Ph2
          u    0.0384    0.0384    0.9993    0.9993
      alpha    1.0000    1.0000    0.0072    0.0072
      theta    0.9540    0.9540    0.2999    0.2999
          q    1.0000    1.0000    0.0094    0.0094
         nz    0.9998    0.9998    0.0204    0.0204


Normalized Longitudinal Residue Angles

                SP1       SP2       Ph1       Ph2
          u  262.4676   97.5324   88.8205  271.1795
      alpha  271.3283   88.6717  268.8577   91.1423
      theta  251.9337  108.0663  350.5027    9.4973
          q   25.3697  334.6303   87.1596  272.8404
         nz  271.3630   88.6370   91.8975  268.1025
```

Figure 16. Archangel residue matrix display

The first matrix is the magnitude of the corresponding residue, while the second is the angle by which it departs the appropriate root. In addition to the numerical display of the normalized

residues, each of these is combined with their appropriate root in a graphical display called the *Modal Root/Residue Display*. Figure 17 depicts a typical modal root/residue display.

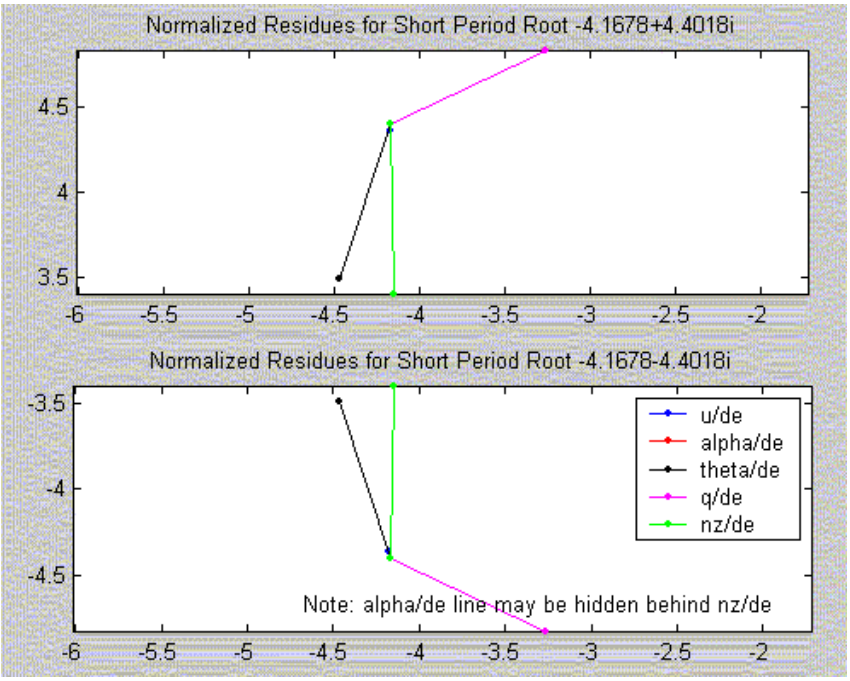

Figure 17. Archangel modal root/residue display

Residue and Additional Analyses Option 5 - Display effect of delay on poles
Selecting option 5, display effect of delay on poles, opens another menu listing all the transfer functions, starting with longitudinal in standard order, then lateral (aileron) and lateral (rudder), both in standard order. The last three menu items will return you to the "Residue and additional analyses" menu, escape to the MatLab command line, and return to the "Archangel main menu", respectively.

When you select a transfer function from this menu, you need to enter the amount of system delay you want to add (it must be positive and not zero). Archangel will display a root locus plot containing the original (red) and the delayed (blue) root loci and their movement as gain is increased (see Figure 18). Note that as delay is added, the system gets worse as we should expect.

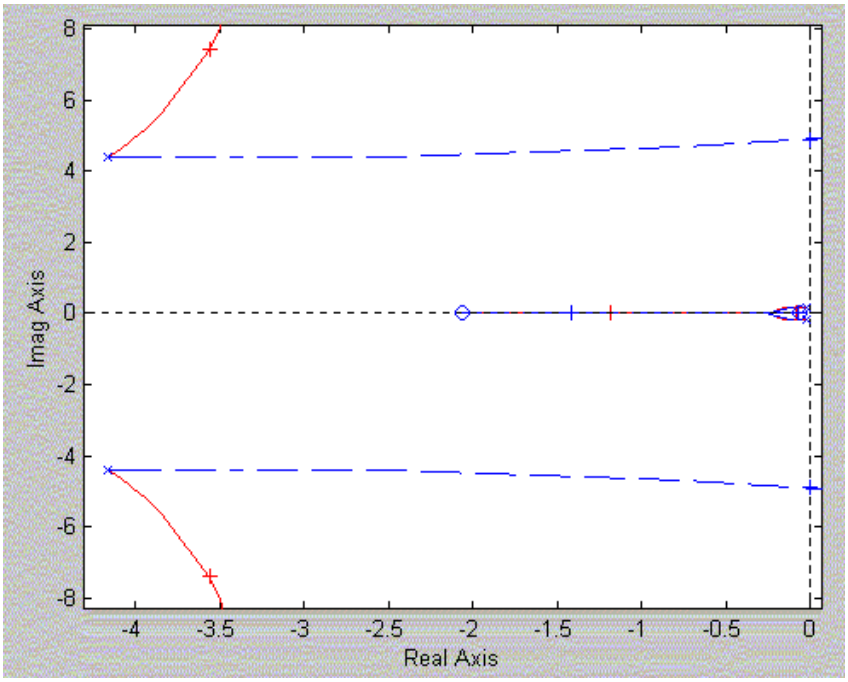

Figure 18. Archangel delayed root locus plot

This plot is displayed using the Aerocontrols toolbox. To close it, press the "Enter" key; you will be returned to the "Display effect of delay on roots" menu.

Residue and Additional Analyses Option 6 - Display effect of delay on short period residues
Option 6 will open a short menu of only the longitudinal transfer functions in standard order. The last three options on this menu will allow return to the "Residue and additional analyses" menu, escape to the MatLab command line, and return to the "Archangel main menu", respectively.

When you select a transfer function from this menu, you need to enter the amount of system delay you want to add (it must be positive and not zero). Archangel will display two numerical sets of residues (see Figure 19). Like roots, residues come in pairs; one in the positive imaginary plane, the other in the negative imaginary plane. Therefore, there are two sets displayed here: one for each residue. In each set displayed, the first is the undelayed residue and the second the delayed residue.

```
First
Undelayed and Delayed SP residues
  -0.2958 - 0.9069i

  -0.6713 - 0.7127i

Second
Undelayed and Delayed SP residues
  -0.2958 + 0.9069i

  -0.6713 + 0.7127i
```

Figure 19. Archangel numerical display of delayed/undelayed short period residues

You can see that as delay is added, the residue real parts become more negative and their imaginary parts become less negative, giving the effect that the residues are moving to the left and down. We also know that as delay is increased, the system becomes more difficult to handle. Therefore, as these residues move with increased delay, the less stable the aircraft. Short period residues from some transfer functions have more effect depending upon the flight condition: θ / δ_e residues are more important to aircraft handling during category C flight operations, while N_z / δ_e residues are more important during category B operations.

Pressing the "Enter" key will show a graphic comparison of the delayed and undelayed residues, an example of which is shown in Figure 20. The residues are shown radiating out from their related short period roots to help the student understand the effect of the residue on the root.

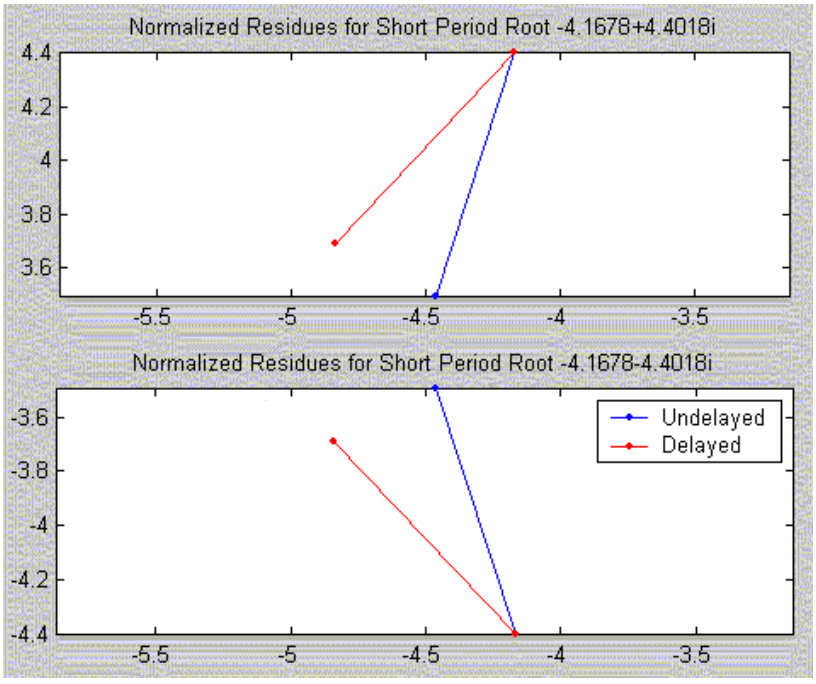

Figure 20. Archangel graphic display of delayed/undelayed short period residues

Residue and Additional Analyses Option 7 - Display effect of delay on phugoid residues
Option 7 will open a menu listing only the longitudinal transfer functions in standard order. The last three options on this menu will allow return to the "Residue and additional analyses" menu, escape to the MatLab command line, and return to the "Archangel main menu", respectively.

When you select a transfer function from this menu, you need to enter the amount of system delay you want to add (it must be positive and not zero). Archangel will display two numerical sets of residues associated with the aircraft phugoid mode similar to the short period delayed residue display. When the "Enter" key is pressed, Archangel will show the graphic comparison of the delayed and undelayed residues as compared to the appropriate phugoid roots. See Figures 19 and 20 for what these displays will resemble.

Residue and Additional Analyses Option 8 - Display effect of delay on Dutch roll residues
Option 8 will open a menu of only the lateral transfer functions in standard order. The last three options on this menu will allow return to the "Residue and additional analyses" menu, escape to the MatLab command line, and return to the "Archangel main menu", respectively.

When you select a transfer function from this menu, you need to enter the amount of system delay you want to add (it must be positive and not zero). Archangel will display two numerical sets of residues associated with the aircraft Dutch roll mode similar to the short period delayed residue display. When the "Enter" key is pressed, Archangel will show the graphic comparison of the delayed and undelayed residues as compared to the appropriate Dutch roll roots. See Figures 19 and 20 for what these displays will resemble.

Residue and Additional Analyses Option 9 - Display effect of delay on roll residues
Option 9 will open a menu listing only the lateral transfer functions in standard order. The last three options on this menu will allow return to the "Residue and additional analyses" menu, escape to the MatLab command line, and return to the "Archangel main menu", respectively.

When you select a transfer function from this menu, you need to enter the amount of system delay you want to add (it must be positive and not zero). Archangel will display two numerical sets of residues associated with the aircraft roll mode similar to the short period delayed residue display. When the "Enter" key is pressed, Archangel will show the graphic comparison of the delayed and undelayed residues as compared to the appropriate roll root. See Figures 19 and 20 for what these displays will resemble.

Residue and Additional Analyses Option 10 - Display effect of delay on spiral residues
Option 10 will open a menu of only the lateral transfer functions in standard order. The last three options on this menu will allow return to the "Residue and additional analyses" menu, escape to the MatLab command line, and return to the "Archangel main menu", respectively.

When you select a transfer function from this menu, you need to enter the amount of system delay you want to add (it must be positive and not zero). Archangel will display two numerical sets of residues associated with the aircraft spiral mode similar to the short period delayed residue display. When the "Enter" key is pressed, Archangel will show the graphic comparison of the delayed and undelayed residues as compared to the appropriate spiral root. See Figures 19 and 20 for what these displays will resemble.

Residue and Additional Analyses Option 11 - Display Modal Controllability matrix, Eigenspace and MatLab calculated residues
This option will display each of these matrices in succession. These matrices are a new way of calculating and displaying residues, and are based on the original state-space equation. First, the A matrix can be written as a combination of its eigenvalue (Λ) and eigenvector (E) matrices

$$A = E\Lambda E^{-1}$$

Substituting this into the original state space equation, performing several mathematical gymnastics, and solving for the general transfer function, we get

$$\left.\frac{x_i(s)}{u_j(s)}\right|_{i=1,n} = E(sI-\Lambda)^{-1}(E^{-1}b_j)$$

The eigenvector matrix, *E,* can be broken down into a series of column vectors, $e_1 \ldots e_n$. Additionally, based on mathematical definition, the inverse eigenvector matrix can be written as a series of transposed row vectors, $m_1^{\mathrm{T}} \ldots m_n^{\mathrm{T}}$, giving us a new form.

$$\left.\frac{x_i(s)}{u_j(s)}\right|_{i=1,n} = \begin{bmatrix} e_1 & e_2 & \cdots & e_n \end{bmatrix} (sI-\Lambda)^{-1} \begin{bmatrix} m_1^T b_j \\ \vdots \\ m_n^T b_j \end{bmatrix}$$

Rearranging and consolidating, the transfer function takes the same form as the residue equation

$$\left.\frac{x_i(s)}{u_j(s)}\right|_{i=1,n} = \sum_{k=1}^{n} e_{ik} \frac{(m_i^T b_j)}{(sI-\Lambda)} = \sum_{k=1}^{n} \frac{R_{\lambda_k ij}}{(sI-\Lambda)}$$

This shows the relationship between the transfer function, eigenvectors and residues. The combination $m_i^T b_j$ above is called the *modal controllability vector*, and it provides insight into the how easily a particular mode of motion is controllable by the system. The higher the relative value in this vector for a particular control u_j, the more easily controllable the associated mode of motion will be using that control (elevator, aileron, rudder, etc.). This equation shows the residues $R_{\lambda_k ij}$ for the transfer function are the eigenvector matrix elements scaled by the modal controllability vector for control u_j.

This option will first display the modal controllability vector as in Figure 21.

```
Modal_Controllability_Matrix =

  1.0e+002 *

   0.1575 - 0.1792i
   0.1575 + 0.1792i
  -1.1977 - 1.6139i
  -1.1977 + 1.6139i
```

Figure 21. Archangel modal controllability vector display

After pressing the "Enter" key, Archangel will present a comparison of the eigenspace analysis residue matrix calculations to those obtained using MatLab tools, as shown in Figure 22.

```
Eigenspace_Residue_Matrix =

  1.0e+002 *

   0.0101 + 0.0766i   0.0101 - 0.0766i  -0.0414 - 2.0093i  -0.0414 + 2.0093i
  -0.0010 + 0.0444i  -0.0010 - 0.0444i   0.0000 + 0.0003i   0.0000 - 0.0003i
   0.0112 + 0.0343i   0.0112 - 0.0343i  -0.0112 + 0.0019i  -0.0112 - 0.0019i
  -0.1973 - 0.0936i  -0.1973 + 0.0936i  -0.0001 - 0.0020i  -0.0001 + 0.0020i


Calculated_Residues =

  1.0e+002 *

   0.0101 + 0.0766i   0.0101 - 0.0766i  -0.0414 - 2.0093i  -0.0414 + 2.0093i
  -0.0010 + 0.0444i  -0.0010 - 0.0444i   0.0000 + 0.0003i   0.0000 - 0.0003i
   0.0112 + 0.0343i   0.0112 - 0.0343i  -0.0112 + 0.0019i  -0.0112 - 0.0019i
  -0.1973 - 0.0936i  -0.1973 + 0.0936i  -0.0001 - 0.0020i  -0.0001 + 0.0020i
```

Figure 22. Archangel residue calculation method comparison

The first matrix shown is that calculated using the eigenspace analysis method. The second is calculated using the native residue command contained within MatLab. This validates the use of either method for residue calculation.

Appendix A - Archangel Variables

Variable Name	***Description***
Alat	Lateral A matrix
Along	Longitudinal A matrix
BW	Bandwidth, lesser of 1) the frequency where gain is 6dB higher than gain where the phase angle = -180°, or 2) the frequency where phase = -135°
Blat	Lateral B matrix
Blong	Longitudinal B matrix
Btodaden	sideslip angle to aileron deflection transfer function denominator
Btodanum	sideslip angle to aileron deflection transfer function numerator
Btodrden	sideslip angle to rudder deflection transfer function denominator
Btodrnum	sideslip angle to rudder deflection transfer function numerator
CAP	Control Anticipation Parameter
CAPlev	Control Anticipation Parameter criterion assessed FHQ level
CD1	steady-state drag coefficient
CDde	drag due to horizontal tail surface non-dimensional derivative
CL1	steady-state lift coefficient
CLde	lift due to horizontal tail surface non-dimensional derivative
Cda	drag due to change in angle of attack non-dimensional derivative
Cdu	drag due to change in velocity non-dimensional derivative
ClB	rolling moment due to change in sideslip angle non-dimensional derivative
Cla	lift due to change in angle of attack non-dimensional derivative
Cladot	lift due to change in angle of attack rate of change non-dimensional derivative
Clat	Lateral C matrix
CldA	rolling moment due to aileron deflection non-dimensional derivative
CldR	rolling moment due to rudder deflection non-dimensional derivative
Clong	Longitudinal C matrix
Clp	rolling moment due to change in roll rate non-dimensional derivative
Clq	lift due to change in pitch rate non-dimensional derivative
Clr	rolling moment due to change in yaw rate non-dimensional derivative
Clu	lift due to change in velocity non-dimensional derivative
Cm1	steady-state mass coefficient
CmT1	steady-state lateral axis thrust coefficient
CmTa	pitching moment due to thrust along the angle of attack path non-dimensional derivative
CmTu	pitching moment due to thrust along longitudinal axis non-dimensional derivative
Cma	pitching moment due to angle of attack non-dimensional derivative
Cmadot	pitching moment due to angle of attack rate of change non-dimensional derivative
Cmde	pitching moment due to elevator deflection non-dimensional derivative
Cmq	pitching moment due to pitch rate non-dimensional derivative

Variable Name	*Description*
Cmu	pitching moment due to velocity non-dimensional derivative
CnB	yawing moment due to change in sideslip angle non-dimensional derivative
CndA	yawing moment due to aileron deflection non-dimensional derivative
CndR	yawing moment due to rudder deflection non-dimensional derivative
Cnp	yawing moment due to change in roll rate non-dimensional derivative
Cnr	yawing moment due to change in yaw rate non-dimensional derivative
Ctx1	steady-state longitudinal axis thrust coefficient
Ctxu	change in thrust due to change in longitudinal axis velocity non-dimensional derivative
CyB	side force due to change in sideslip angle non-dimensional derivative
CydA	side force due to aileron deflection non-dimensional derivative
CydR	side force due to rudder deflection non-dimensional derivative
Cyp	side force due to change in roll rate non-dimensional derivative
Cyr	side force due to change in yaw rate non-dimensional derivative
DBCL	magnitude of the closed loop frequency response, from Mil-Std Closed Loop criterion handling qualities rating
Dlat	Lateral D matrix
DlaydADeRes	matrix of delayed α / δ_e transfer function residues
DlaydBDaRes	matrix of delayed β / δ_a transfer function residues
DlaydBDrRes	matrix of delayed β / δ_r transfer function residues
DlaydNzDeRes	matrix of delayed Nz / δ_e transfer function residues
DlaydPDaRes	matrix of delayed p / δ_a transfer function residues
DlaydPDrRes	matrix of delayed p / δ_r transfer function residues
DlaydPhiDaRes	matrix of delayed ϕ / δ_a transfer function residues
DlaydPhiDrRes	matrix of delayed ϕ / δ_r transfer function residues
DlaydPsiDaRes	matrix of delayed ψ / δ_a transfer function residues
DlaydPsiDrRes	matrix of delayed ψ / δ_r transfer function residues
DlaydQDeRes	matrix of delayed q / δ_e transfer function residues
DlaydRDaRes	matrix of delayed r / δ_a transfer function residues
DlaydRDrRes	matrix of delayed r / δ_r transfer function residues
DlaydThDeRes	matrix of delayed θ / δ_e transfer function residues
DlaydUDeRes	matrix of delayed u / δ_e transfer function residues
Dlong	Longitudinal D matrix
FREQ	transpose of “freq” (see below) vector

Variable Name	***Description***
GAIN	θ / δ_e response magnitude
Ixx	mass moment of inertia about the longitudinal (x) axis
Ixz	*x-z* product of inertia
Iyy	mass moment of inertia about the lateral (y) axis
Izz	mass moment of inertia about the vertical (z) axis
LEAD	Neal-Smith criterion resultant required pilot lead in degrees
Lb	rolling moment due to change in sideslip angle stability derivative
Lbs	`(Lb)/((1-(Ixz^2/(Ixx*Izz))))`
LdA	rolling moment due to aileron deflection stability derivative
LdAs	`(LdA)/((1-(Ixz^2/(Ixx*Izz))))`
LdR	rolling moment due to rudder deflection stability derivative
LdRs	`(LdR)/((1-(Ixz^2/(Ixx*Izz))))`
Lp	rolling moment due to change in roll rate stability derivative
Lps	`(Lp)/((1-(Ixz^2/(Ixx*Izz))))`
Lr	rolling moment due to change in yaw rate stability derivative
Lrs	`(Lr)/((1-(Ixz^2/(Ixx*Izz))))`
MAG	θ / δ_e response magnitude in dB
Mde	pitching moment due to elevator deflection stability derivative
Mq	pitching moment due to change in pitch rate stability derivative
Mu	pitching moment due to change in longitudinal velocity stability derivative
Mw	pitching moment due to change in vertical velocity stability derivative
Mwd	pitching moment due to change in vertical acceleration stability derivative
Nb	yaw moment due to change in sideslip angle stability derivative
Nbs	`(Nb)/((1-(Ixz^2/(Izz*Ixx))))`
NdA	yaw moment due to change aileron deflection stability derivative
NdAs	`(NdA)/((1-(Ixz^2/(Izz*Ixx))))`
NdR	yaw moment due to change rudder deflection stability derivative
NdRs	`(NdR)/((1-(Ixz^2/(Izz*Ixx))))`
Np	yaw moment due to change in roll rate stability derivative
Nps	`(Np)/((1-(Ixz^2/(Izz*Ixx))))`
Nr	yaw moment due to change in yaw rate stability derivative
Nrs	`(Nr)/((1-(Ixz^2/(Izz*Ixx))))`
Nz_GAIN	Nz / δ_e response magnitude
Nz_MAG	Nz / δ_e response magnitude in dB
Nz_PHASE	Nz / δ_e response phase in degrees
PHASE	θ / δ_e response phase in degrees
PHCL	phase of the closed loop frequency response, from Mil-Std Closed Loop criterion handling qualities rating
Q	flight dynamic pressure
RES	Neal-Smith criterion resultant resonance peak in dB

Variable Name	*Description*
S	aircraft wing area
TP	estimated equivalent time delay in seconds, used in Mil-Std Bandwidth criterion assessment
U	aircraft forward velocity
UndlaydADeRes	matrix of undelayed α / δ_e transfer function residues
UndlaydBDaRes	matrix of undelayed β / δ_a transfer function residues
UndlaydBDrRes	matrix of undelayed β / δ_r transfer function residues
UndlaydNzDeRes	matrix of undelayed Nz / δ_e transfer function residues
UndlaydPDaRes	matrix of undelayed p / δ_a transfer function residues
UndlaydPDrRes	matrix of undelayed p / δ_r transfer function residues
UndlaydPhiDaRes	matrix of undelayed ϕ / δ_a transfer function residues
UndlaydPhiDrRes	matrix of undelayed ϕ / δ_r transfer function residues
UndlaydPsiDaRes	matrix of undelayed ψ / δ_a transfer function residues
UndlaydPsiDrRes	matrix of undelayed ψ / δ_r transfer function residues
UndlaydQDeRes	matrix of undelayed q / δ_e transfer function residues
UndlaydRDaRes	matrix of undelayed r / δ_a transfer function residues
UndlaydRDrRes	matrix of undelayed r / δ_r transfer function residues
UndlaydThDeRes	matrix of undelayed θ / δ_e transfer function residues
UndlaydUDeRes	matrix of undelayed u / δ_e transfer function residues
W	aircraft weight
WIN	Neal-Smith criterion resultant frequency vector for closed loop response
Xde	longitudinal force due to elevator deflection stability derivative
Xtu	longitudinal force due to change in longitudinal thrust stability derivative
Xu	longitudinal force due to change in longitudinal velocity stability derivative
Xw	longitudinal force due to change in vertical velocity stability derivative
Yb	lateral force due to change in sideslip angle stability derivative
YdA	lateral force due to aileron deflection stability derivative
YdR	lateral force due to rudder deflection stability derivative
Yp	lateral force due to change in roll rate stability derivative
Yr	lateral force due to change in yaw rate stability derivative
Zde	vertical force due to elevator deflection stability derivative
Zq	vertical force due to change in pitch rate stability derivative
Zu	vertical force due to change in longitudinal velocity stability derivative
Zw	vertical force due to change in vertical velocity stability derivative

Variable Name	***Description***
aKs	direct term of the α / δ_e partial fraction expansion
aPoles	poles of the α / δ_e partial fraction expansion
aResidues	residues of the α / δ_e partial fraction expansion
alphatodeden	angle of attack to elevator deflection transfer function denominator
alphatodenum	angle of attack to elevator deflection transfer function numerator
altitude	aircraft altitude above sea-level
b	aircraft wingspan
baKs	direct term of the β / δ_a partial fraction expansion
baPoles	poles of the β / δ_a partial fraction expansion
baResidues	residues of the β / δ_a partial fraction expansion
bandwidth	same as "BW" above
brKs	direct term of the β / δ_r partial fraction expansion
brPoles	poles of the β / δ_r partial fraction expansion
brResidues	residues of the β / δ_r partial fraction expansion
bwlev	Mil-Std Bandwidth criterion assessed FHQ level
category	flight phase category C subcategory (landing (1) or other than landing (2))
cbar	aircraft wing mean aerodynamic chord
class	aircraft class group
clooplev	Mil-Std Closed Loop criterion assessed FHQ level
daResMatrix	matrix of the δ_a (aileron dependent) transfer function residues
dbcl	magnitude of the closed loop frequency response, from Neal-Smith criterion handling qualities rating
deResMatrix	matrix of the δ_e (elevator dependent) transfer function residues
delay	user specified delay to add to selected transfer functions
drResMatrix	matrix of the δ_r (rudder dependent) transfer function residues
faKs	direct term of the ϕ / δ_a partial fraction expansion
faPoles	poles of the ϕ / δ_a partial fraction expansion
faResidues	residues of the ϕ / δ_a partial fraction expansion
frKs	direct term of the ϕ / δ_r partial fraction expansion
frPoles	poles of the ϕ / δ_r partial fraction expansion
frResidues	residues of the ϕ / δ_r partial fraction expansion
freq	logarithmic frequency vector, spanning 0.1-100 in 400 discrete steps
g	gravitational acceleration (32.2 ft/sec^2 or 9.8 m/sec^2)
latFREQ	transpose of "latfreq" (see below) vector

Variable Name	*Description*
latGAIN	ϕ / δ_e response magnitude
latMAG	ϕ / δ_e response magnitude in dB
latPHASE	ϕ / δ_e response phase in degrees
latfreq	logarithmic frequency vector, spanning 0.1-100 in 400 discrete steps
latrslev	lateral Smith-Geddes criterion FHQ level
latw	lateral logarithmic frequency response vector (see "latfreq" above)
lead	same as "LEAD"
mass	aircraft mass
northroplev	Northrop criterion assessed FHQ level
noveralpha	variable used to calculate the CAP
nslev	Neal-Smith criterion assessed FHQ level
nzKs	direct term of the Nz / δ_e partial fraction expansion
nzPoles	poles of the Nz / δ_e partial fraction expansion
nzResidues	residues of the Nz / δ_e partial fraction expansion
nztodeden	vertical acceleration to elevator deflection transfer function denominator
nztodenum	vertical acceleration to elevator deflection transfer function numerator
oneoverTtheta2	numerator time constant for pitch angle short period approximation
p	`wnsp*(1/oneoverTtheta2)`, used to determine Mil-Std ω_n (short period), $T_{\theta 2}$ criterion assessment
paKs	direct term of the p / δ_a partial fraction expansion
paPoles	poles of the p / δ_a partial fraction expansion
paResidues	residues of the p / δ_a partial fraction expansion
phase	flight phase category (A, B, C)
phcl	same as "PHCL"
phi_ach	average Cooper-Harper rating for results of the ϕ / δ_a TF analysis
phiph_bw	roll attitude criterion function (phase of ϕ / δ_a) bandwidth frequency
phtodaden	roll angle to aileron deflection transfer function denominator
phitodadentd	delayed roll angle to aileron deflection transfer function denominator
phitodanum	roll angle to aileron deflection transfer function numerator
phitodanumtd	delayed roll angle to aileron deflection transfer function numerator
phitodrden	roll angle to rudder deflection transfer function denominator
phitodrnum	roll angle to rudder deflection transfer function numerator
pio	Smith-Geddes with PIO criterion assessed FHQ level
prKs	direct term of the p / δ_r partial fraction expansion
prPoles	poles of the p / δ_r partial fraction expansion

Variable Name	*Description*
prResidues	residues of the p/δ_r partial fraction expansion
ptodaden	roll rate to aileron deflection transfer function denominator
ptodanum	roll rate to aileron deflection transfer function numerator
ptodrden	roll rate to rudder deflection transfer function denominator
ptodrnum	roll rate to rudder deflection transfer function numerator
qKs	direct term of the q/δ_e partial fraction expansion
qPoles	poles of the q/δ_e partial fraction expansion
qResidues	residues of the q/δ_e partial fraction expansion
qtodeden	pitch rate to elevator deflection transfer function denominator
qtodenum	pitch rate to elevator deflection transfer function numerator
raKs	direct term of the r/δ_a partial fraction expansion
raPoles	poles of the r/δ_a partial fraction expansion
raResidues	residues of the r/δ_a partial fraction expansion
rho	air density at current altitude
rrKs	direct term of the r/δ_r partial fraction expansion
rrPoles	poles of the r/δ_r partial fraction expansion
rrResidues	residues of the r/δ_r partial fraction expansion
rs_nz	acceleration criterion function (phase of Nz/δ_e) at bandwidth frequency
rslev	Smith-Geddes criterion assessed FHQ level
rtodaden	yaw rate to aileron deflection transfer function denominator
rtodanum	yaw rate to aileron deflection transfer function numerator
rtodrden	yaw rate to rudder deflection transfer function denominator
rtodrnum	yaw rate to rudder deflection transfer function numerator
siaKs	direct term of the ψ/δ_a partial fraction expansion
siaPoles	poles of the ψ/δ_a partial fraction expansion
siaResidues	residues of the ψ/δ_a partial fraction expansion
sirKs	direct term of the ψ/δ_r partial fraction expansion
sirPoles	poles of the ψ/δ_r partial fraction expansion
sirResidues	residues of the ψ/δ_r partial fraction expansion
sitodaden	yaw angle to aileron deflection transfer function denominator
sitodanum	yaw angle to aileron deflection transfer function numerator
sitodrden	yaw angle to rudder deflection transfer function denominator
sitodrnum	yaw angle to rudder deflection transfer function numerator
stab	SAD file input matrix

Variable Name	***Description***
thKs	direct term of the θ / δ_e partial fraction expansion
thPoles	poles of the θ / δ_e partial fraction expansion
thResidues	residues of the θ / δ_e partial fraction expansion
tha_ach	average Cooper-Harper rating for results of the θ / δ_e TF analysis
thaph_bw	pitch attitude criterion function (phase of θ / δ_e) bandwidth frequency
theta1	aircraft pitch angle
thtodeden	pitch angle to elevator deflection transfer function denominator
thtodedentd	delayed pitch angle to elevator deflection transfer function denominator
thtodenum	pitch angle to elevator deflection transfer function numerator
thtodenumtd	delayed pitch angle to elevator deflection transfer function numerator
uKs	direct term of the u / δ_e partial fraction expansion
uPoles	poles of the u / δ_e partial fraction expansion
uResidues	residues of the u / δ_e partial fraction expansion
utodeden	velocity to elevator deflection transfer function denominator
utodenum	velocity to elevator deflection transfer function numerator
w	logarithmic frequency response vector (see "freq" above)
win	same as "WIN"
wndr	approximate Dutch Roll natural frequency
wndract	actual Dutch Roll natural frequency
wnlev	Mil-Std ω_n (short period), $T_{\theta 2}$ criterion assessed FHQ rating level
wnp	approximated phugoid natural frequency
wnpact	actual phugoid natural frequency
wnsp	approximated short period natural frequency
wnspact	actual short period natural frequency
zdr	approximate Dutch Roll damping ratio
zdract	actual Dutch Roll damping ratio
zp	approximated phugoid damping ratio
zpact	actual phugoid damping ratio
zsp	approximated short period damping ratio
zspact	actual short period damping ratio